Engineering Case Library

ECL 181

A FOUR BARREL STEP-AND-REPEAT CAMERA

Paul Piper was hired by the Friden Research Center to design, develop and produce a microphotographic camera for the production of final stage integrated circuit masks. Piper's problems are described from the management decision to make instead of buying the camera through the design to the testing and modifications of the unit.

 Prepared by G. Kardos with financial support from the National Science Foundation. This is a condensation of a case history written by engineering students C. J. McMills, G. R. Mehta, and F. A. Wile under the supervision of Professor R. F. Steidel, Jr. at the University of California at Berkeley.

A FOUR BARREL STEP-AND-REPEAT CAMERA

In the mid-sixties the Friden Division of the Singer Corporation designed, built, and marketed their first all electronic calculator. The electronic unit was such a success that in the first quarter of 1968 they discontinued development of all new electro-mechanical calculators. Keen competition from Japanese and American electronics firms led Friden to decide that it would be necessary to develop their own integrated circuit capability. The use of integrated circuits for the electronics also offered obvious technical and cost advantages over other methods.

The electronics industry had started by assembling circuits using vacuum tubes, wires, etc. By the 1950's, this evolved into utilizing solid state components transistors, diodes, and printed circuits, etc. in the assembly. Micro-miniature electronics appeared in the early 1960's and began to hit its stride in the mid-sixties. The principal advantage of this third generation of electronics was in the manufacture of integrated circuits. Up to this point, electronic components had been packaged as individual units and connected together to form the necessary circuits. With integrated circuits, the individual components are fabricated simultaneously with their inter-connections. Integrated circuits will contain 100 to 1000 complete circuits in a unit the size of an existing transistor. The benefits are so great that, as Paul Piper of the Friden Research Center points out, "If the electronic firms in this country don't get on the stick, they are going to be out in the cold. We are going to see, in the next few years, big companies going bankrupt if they don't convert, and that time is almost too late."

It is inherent in the manufacture of integrated circuits that the circuit designers and manufacturers be familiar with and produce the transistors and other devices that make up the circuits. The state-of-the-art of circuit manufacturing is given in the following abstract from the Engineering Journal, December 1966.

Microphotographic Methods In Modern Electronic Manufacture

A. Loro

Engineering Journal, December 1966

Figures 1 and 2 give some idea of the scale of modern silicon devices and microcircuits. The high frequency transistor chips shown in Fig. 1 make relatively inefficient use of the material since only about 0.1% of the crystal volume plays an electronically active role, it being impractical to cut, handle, and make electrical connection to much smaller chips. The microcircuit shown in Fig. 2 represents more efficient material usage since it is only about six times the area of the transistor chip but contains 4 transistors, 4 resistors, and 22 junction diodes together with their interconnections.

In order to fabricate a device such as a transistor from a crystal of silicon it is necessary to introduce certain elemental impurities into the crystal in selected areas to generate the pn junctions. It is also necessary to make electrical connection to the separate zones of the crystal so produced. By far the most widely used technology is that known as planar diffusion. In this method the starting point is a highly polished slice of single crystal silicon a few thousandths of an inch (mils) thick and about 1 inch in diameter. A thin skin of the natural silicon dioxide is grown on the polished surface by high temperature oxidation and an array of minute holes are etched through this skin. When the silicon is subsequently exposed at elevated temperatures to an atmosphere containing a desired impurity species, the oxide skin acts like a stencil and allows the impurity to diffuse into the silicon crystal lattice only through the etched holes. The holes may be closed by oxide regrowth and the process repeated, through a new array of holes in spatial relationship to the first array, using a second impurity species. The silicon dioxide remains on the surface of completed devices for protection and insulation, electrical connection being made through further holes etched in it. The contacting metal is applied by vacuum plating over the entire surface and is subsequently formed to the desired pattern by etching away unwanted areas.

In order to make manufacture economically feasible a large number of devices are processed simultaneously on each slice of silicon, which is separated into discrete dies by diamond scribing only after all processing is completed For separate devices such as diodes or transistors as many a 3500 may be fabricated in one square inch of crystal while 600 microcircuits could be accommodated in the same area, representing the equivalent of maybe 20,000 components per square inch.

Since all the etching processes for silicon dioxide and the contact metal are controlled photographically it will be evident that the fabrication of a device requires the use of a series of photographic negatives corresponding in number to the number of etching processes involved, each one having a multiplicity of micro-images precisely located to permit them to be printed sequentially onto the silicon crystal. Each pattern must, therefore, be positioned with respect to others in the series to within tolerances dictated by the particular design. Line widths and clearances commonly used on microcircuits are 0.5 mils while higher frequency transistors may go down to 0.1 mils and laboratory prototypes have been made with some dimensions of less than 0.05 mils. Displacement of any one pattern of a series would result in devices with degraded electrical characteristics or complete failure due to shorting of the rectifying pn junctions. A set of masks for a transistor normally includes four plates whereas a silicon microcircuit requires six or more for its manufacture.

A common starting point in the various methods of preparing masks is the preparation of a set of greatly enlarged patterns of a single device or circuit. Such a set consists of one pattern corresponding to each etching operation in the manufacturing process drawn between 100 and 500 times the final size of the device in order to achieve the necessary accuracy. Such patterns are normally prepared on a high precision drafting machine capable of holding dimensions to within 1-2 mils over an area of 30-40 in. square. In order to obtain the highest image contrast, these patterns are normally prepared as transparencies to be illuminated by transmitted light during photographic reduction. For this purpose a commercial film, consisting of Mylar coated with a thin strippable film of photographically opaque ruby colored plastic, is widely used. The pattern is cut through the plastic coating which is stripped off where not required.

In the majority of processes the next phase is the preparation of a reduced image of the large patterns, usually to about 3 to 10X final device size by one or more stages of photographic reduction. For this purpose a special type of camera is used which is typified by rigid construction and the provision of means for the precise adjustment of copy to plate distance and lens focussing (Fig. 3). The originals are illuminated by large area mercury vapor discharge lamps having a filtered output in the middle green of the visible spectrum. Such equipment is preferably operated in a dust-free air conditioned location, free from vibration and with temperature constant to ± 1°F.

The next step in the process generally involves the multiple printing of each negative onto a single photographic plate. Reduction down to final size may also be carried out at this stage, resulting in the final mask, or postponed to a final stage reduction of the larger multiple image plate. The type of equipment used will be quite different according to which approach is chosen.

The final size step and repeat method has the advantage that microscope type optics can be used to give high image resolution, since only one device area need be covered at one time. However, very precise mechanical construction is required since mechanical errors are reproduced on a one-to-one basis and the lens focus must be held to within a few microns over the entire printing area for optimum image quality. Basically such a machine consists of a reducing optical projector mounted to print onto a plate held on the table of a high precision xy positioner together with suitable equipment to control the table position for each exposure.

The alternative approach of multiple printing at about 10X final size usually involves the use of a step and repeat contact printer. An advantage is that any positional errors will be scaled down during the final reduction but the large

image area to be covered during final reduction (typically at least 1 in. diameter circle) and the continually higher resolution demanded by the device designer severely tax the capabilities of the finest lenses and it seems inevitable that this system will, in time, be entirely superseded by the final size step and repeat methods in which the mechanical positioning problem is more readily solved.

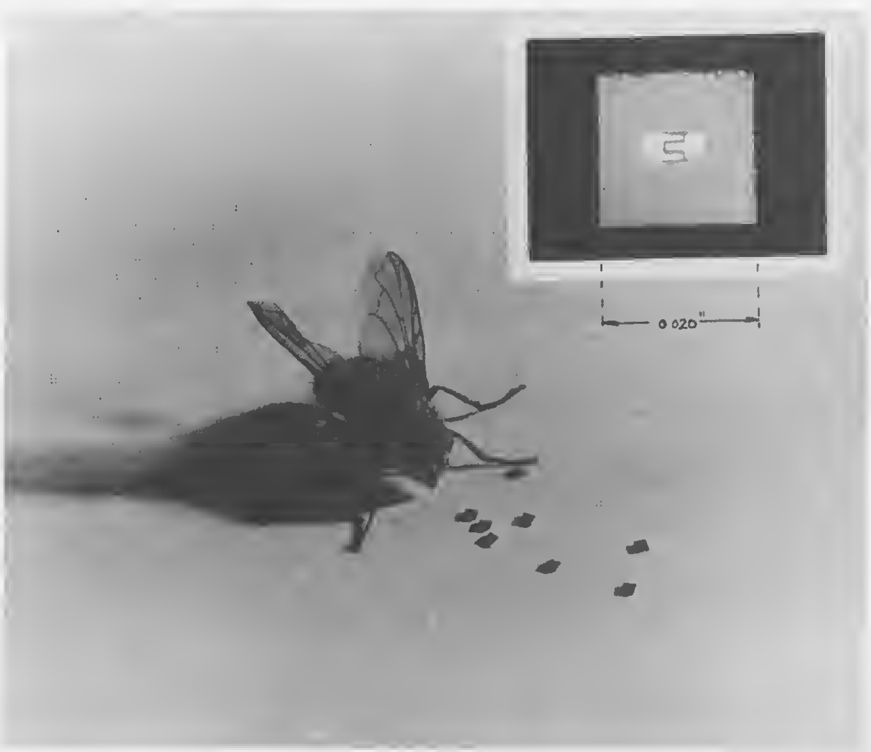
A useful technique which permits precision of alignment independent of the precision of repeat spacing is known as simultaneous stepping. In many devices the active regions occupy only a small fraction of the total area of the silicon crystal (Fig. 1). In such cases all the patterns required to fabricate the device can be accommodated within one repeat area on the crystal. If the original patterns are cut as a single group they may be reduced and stepped to produce a single mask plate which can be used for all etching operations. At each process step only one of the patterns within the group is actually used, the others producing redundant images outside the active device area. This principle is illustrated in Fig. 4. Since the dimensions of each group are identical, alignment of one device automatically gives alignment of all others even if the step and repeat spacing is entirely random, provided that there has been no relative rotation between the negative and the plate during the preparation of the mask.

The advantages of simultaneous stepping can be extended to devices which occupy the whole available area of the crystal (eg. microcircuits) if the separate patterns of the group are spaced apart a distance greater than the total length of the mask. In this case each pattern forms its own separate array which may be recorded on separate plates on a common carrier. The machine shown in Fig. 5 achieves this end by having four separate reducing projectors each containing one pattern negative mounted over a common xy positioner carrying four photographic plates.

In transferring the images from the masks to the semiconductor surface, use is made of photoresists. Their function is to provide an adherent stencil through which the semiconductor, its oxide or an overlying metal film can be etched. They consist of organic materials which can be applied in solution by spin coating, dipping, or spraying, and which react to light in one of two ways. One type is photo-polymerized to render it insoluble in the exposed areas while unexposed materials can be washed away in a solvent developer. This type is most widely used to etch holes through oxide leaving most of the oxide in situ. The other type as coated is insoluble in the developer but is rendered soluble by light exposure. This type is frequently used when most of the etched material is to be removed leaving only islands or narrow lines as in the case of metal contacts and interconnections. The use of both types as described permits the masks to be all of the same contrast, i.e. all having opaque image areas on a clear background. This simplifies visual alignment and eliminates an additional photographic process which would be necessary to produce masks having clear patterns on an opaque background.

Photoresists have their maximum sensitivity in the near U.V. and violet end of the spectrum and are generally exposed using mercury or xenon discharge lamps. Exposure of the photoresist is practically always carried out by contact printing which entails precise alignment of each mask with the preceding set of images while the mask is

Fig. 1. A common housefly gives scale to some silicon U.H.F. transistor chips. Inset: Plan view of a single chip.



very close to, but not touching, the photoresist, followed by making positive contact for exposure in order to obtain the best quality image transfer. In the most critical cases an immersion liquid may be used to fill the gap between mask and photoresist in order to minimize loss of resolution by refraction (variations in silver content cause slight surface contours on the mask emulsion) and printing of spurious images by diffraction at surface defects and foreign particles. In any case, wear on the delicate gelatin emulsion is inevitable and masks must be discarded frequently to minimize disastrous loss of yield in the multi-stage semiconductor process. In order to overcome this problem many manufacturers now use masks consisting of etched metal films on glass substrates made by photolithography from the camera exposed emulsion masters. A ready made metallized glass plate, precoated with photoresist for the fabrication of such masks, will probably be the next commercially available photographic material created specifically for the electronics industry.

It will be obvious that the economic manufacture of semiconductor devices and microcircuits is critically dependent on the utmost attention to detail at every stage of a long and complicated process. The extreme sensitivity of semiconductors to impurities on the submicrogram scale places godliness a poor second to cleanliness in semiconductor manufacture. The aligned etching of six or more arrays each of hundreds of flawless microimages, an extremely difficult feat even in the laboratory, is demanded daily of the microcircuit manufacturer on a mass production scale.

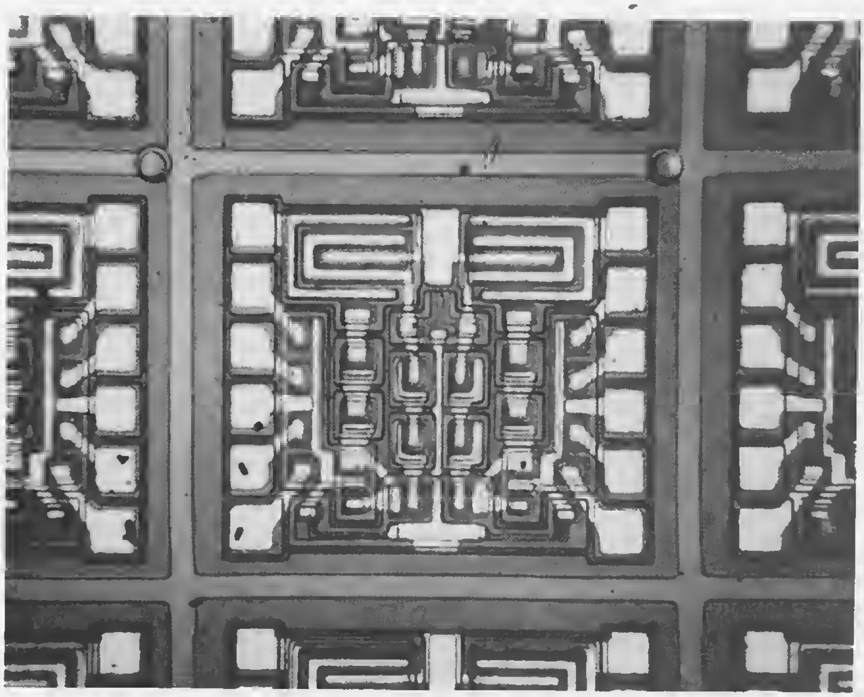
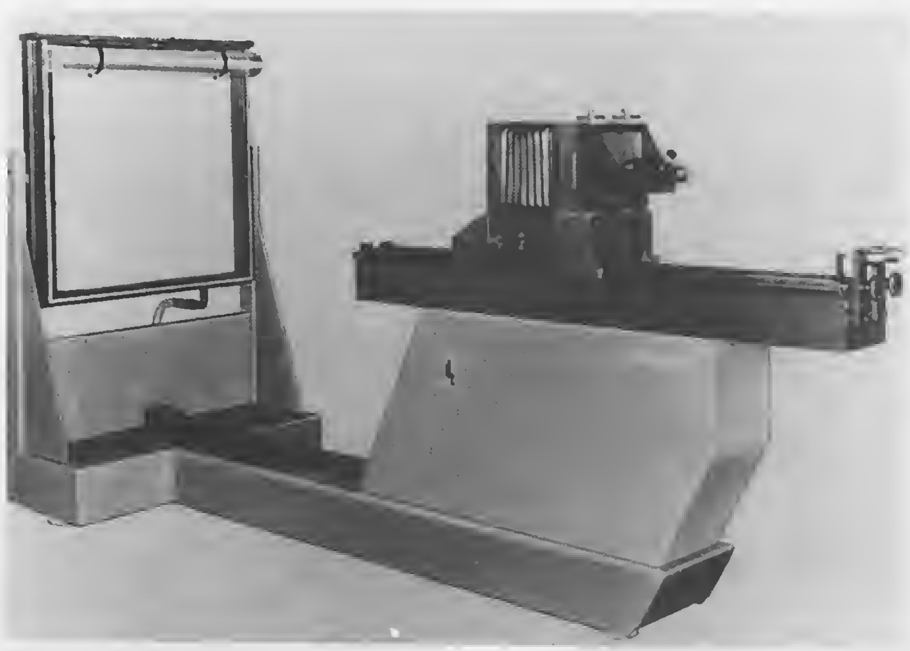


Fig. 2. Part of a slice of diffused silicon microcircuits before cutting. The diffused areas are various shades of grey. The light pattern consists of metallic interconnections.

Fig. 3. Precision reduction camera designed for electronic work (Photo courtesy H. L. C. Engineering).



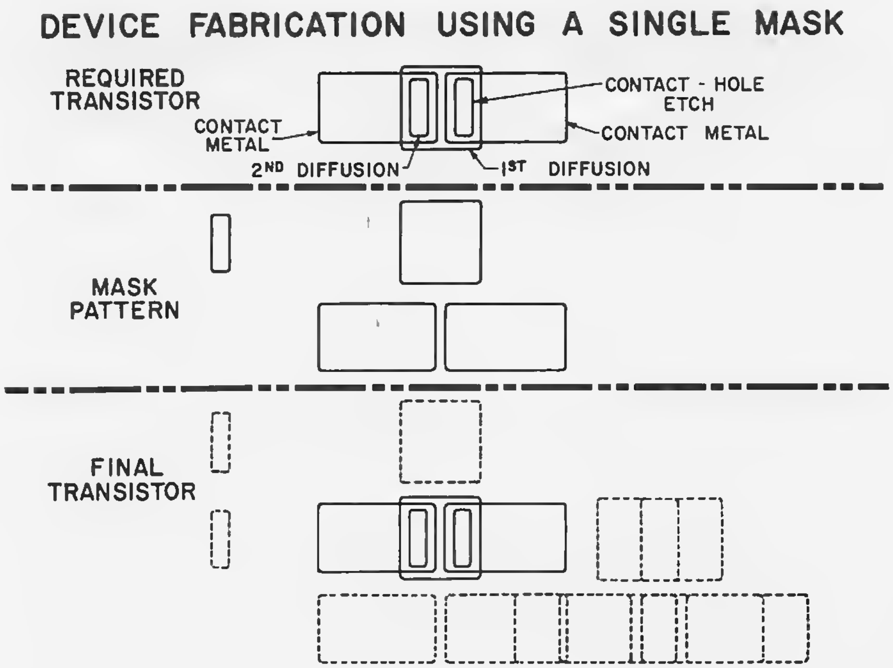


Fig. 4. To produce the transistor (top) the same group of patterns (centre) is printed in a new position at each process step (bottom). Identical displacements occur at every similar group on the mask.

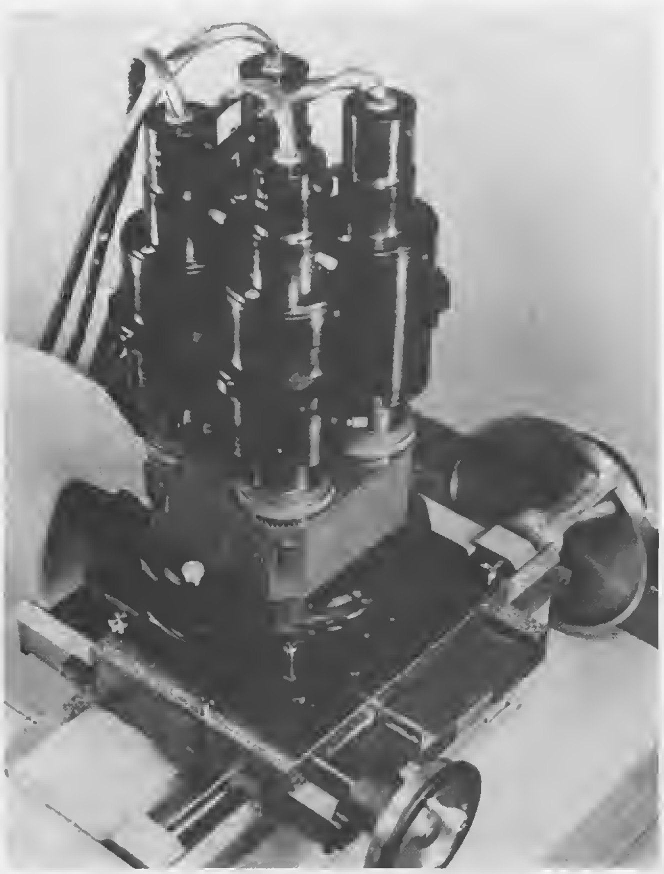


Fig. 5. A photorepeater incorporating four projector barrels which permit simultaneous stepping of four patterns. (Photo courtesy David W. Mann Company.)

Friden, as a subsidiary of Singer Corporation, has many operating divisions. Each division was responsible for its own research, engineering, production, and for showing a profit on its total operation. Early in 1966, Mr. L. P. Robinson, the Friden Vice-President who had been the driving force behind the electronic calculator, saw the need for a research center completely divorced from the operating divisions, devoted to state-of-the-art research. At first, Friden management rejected the idea, since such a center could not show a profit and would thus be an uncontrolled expense burden on the other divisions. Finally, after some revision of his original plans, Mr. Robinson secured Friden and Singer Corporate approval.

The Friden Research Division was formed in June 1960 for the purpose of becoming expert in the field of integrated circuit design and manufacture, but not necessarily to develop immediately useful processes. It had been agreed by management that only by thoroughly understanding the field of integrated circuits could a fully automated manufacturing facility be eventually built, and the cost of this research would have to be recovered by having a more economic production facility.

Mr. Robinson remained a Friden Vice-President but also became Director of Research. There were six major areas of interest, each with a director (Figure 1). Mr. Barney D. Hunt joined the division on October 31, 1966, to become Director of Microcircuits. His responsibilities included microphotography, circuit design and all integrated circuit processes.

The operation of the Research Division was based on Friden's decision to produce integrated circuits internally. While companies were available which did produce integrated circuits to specifications, it was apparent that integrated circuits in Friden products would be an important item and a large part of the cost. The cost of purchasing custom circuits from outside firms as well as length of delivery time would make that option prohibitive. The decision as to whether production equipment would be made or purchased was a compromise. Equipment which was not available or which was critical to the production process would be developed by Friden. Although available equipment could probably be purchased cheaper than developing it, Friden's experience showed that the time required to fully understand critical components of purchased equipment was usually equal to the time to build it. Designing and manufacturing the equipment carried the added advantage of producing a better understanding of the variables involved. The noncritical production equipment would be purchased.

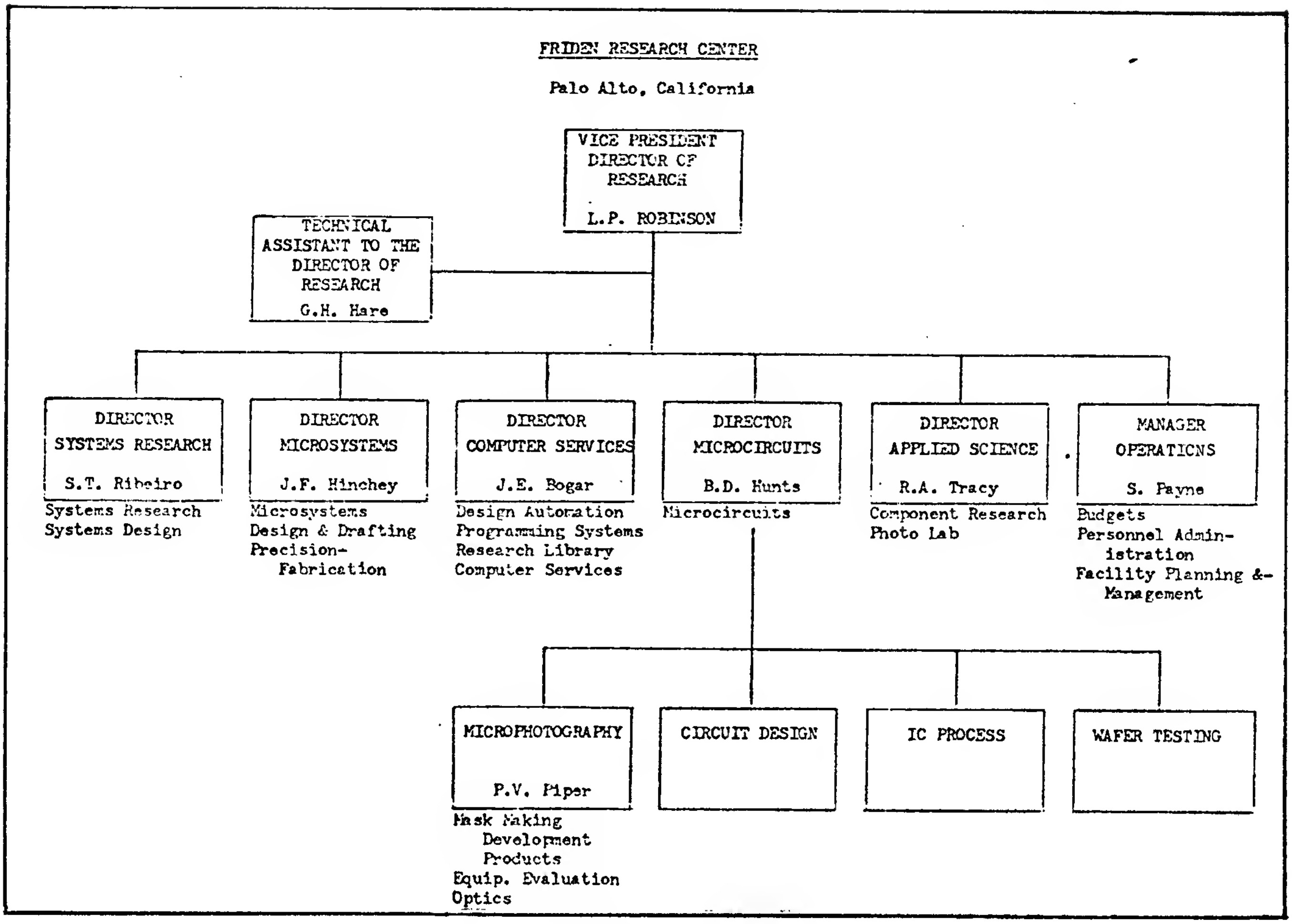


Figure 1

Organization Chart

Since the photo reduction process was essential to microcircuit manufacture (Figures 2 and 3) it was decided to build an extremely accurate step-and-repeat camera for the making of the final production masks. The camera was to replicate the circuit masks from the first reduction. The use of four lenses would provide identical replication of four different masks. Because of the knowledge to be gained in the optics of integrated circuit technology, this camera was one to be built without hope of profit.

By November 14, 1966, a first formal presentation of a masking system was made to management based on a feasibility study conducted by G. Hare and A. Rowland. Some of the conclusions drawn were eventually proved to be in error because of insufficient knowledge of optics. As a result, Paul Piper, a mechanical engineer, was hired on December 5 to take charge of microphotography development. He was to implement the design and production of the step-and-repeat camera.

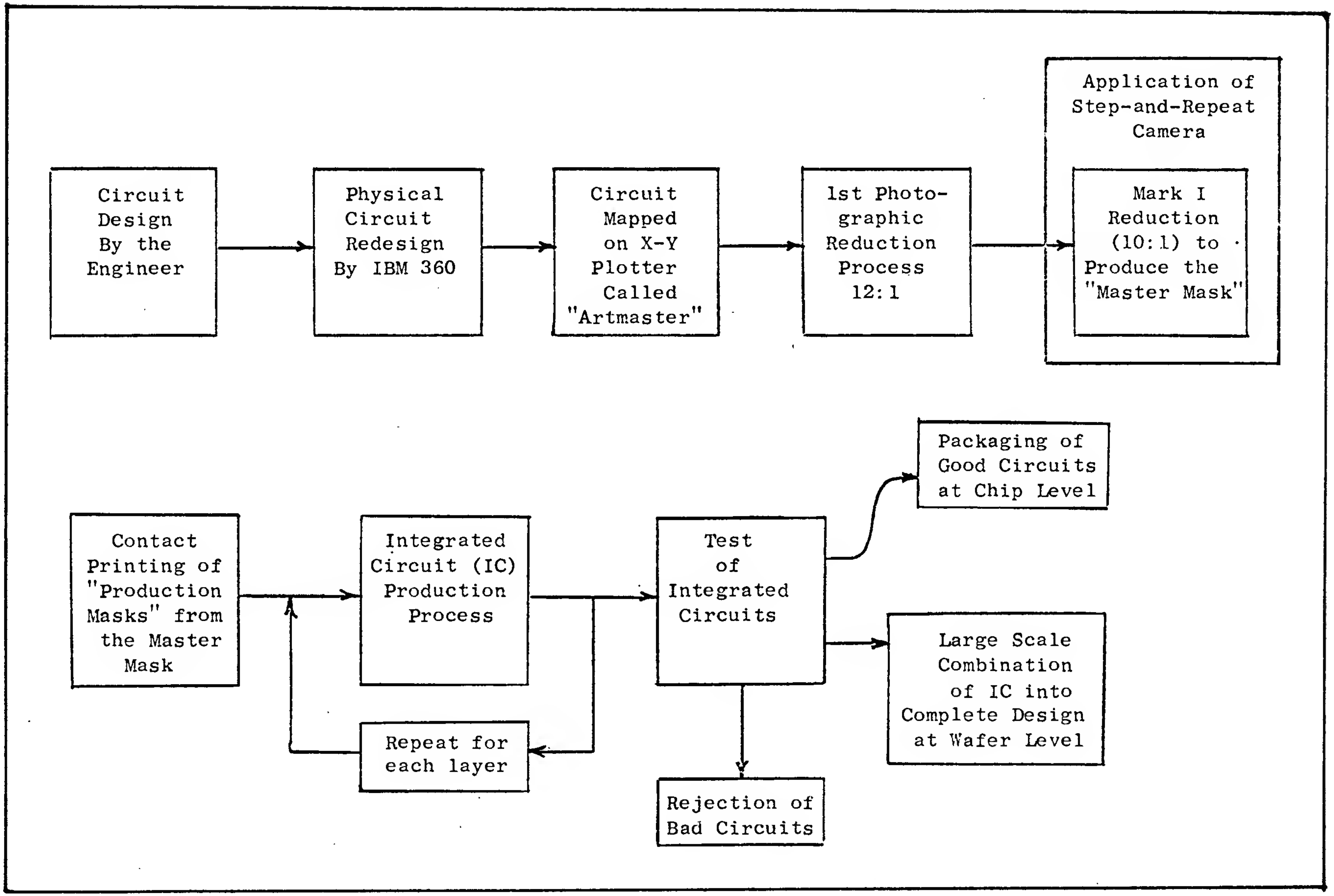


Figure 2

Step-and-Repeat 4-Barrel Camera
Process Flow Diagram for the Manufacture of Integrated Circuits

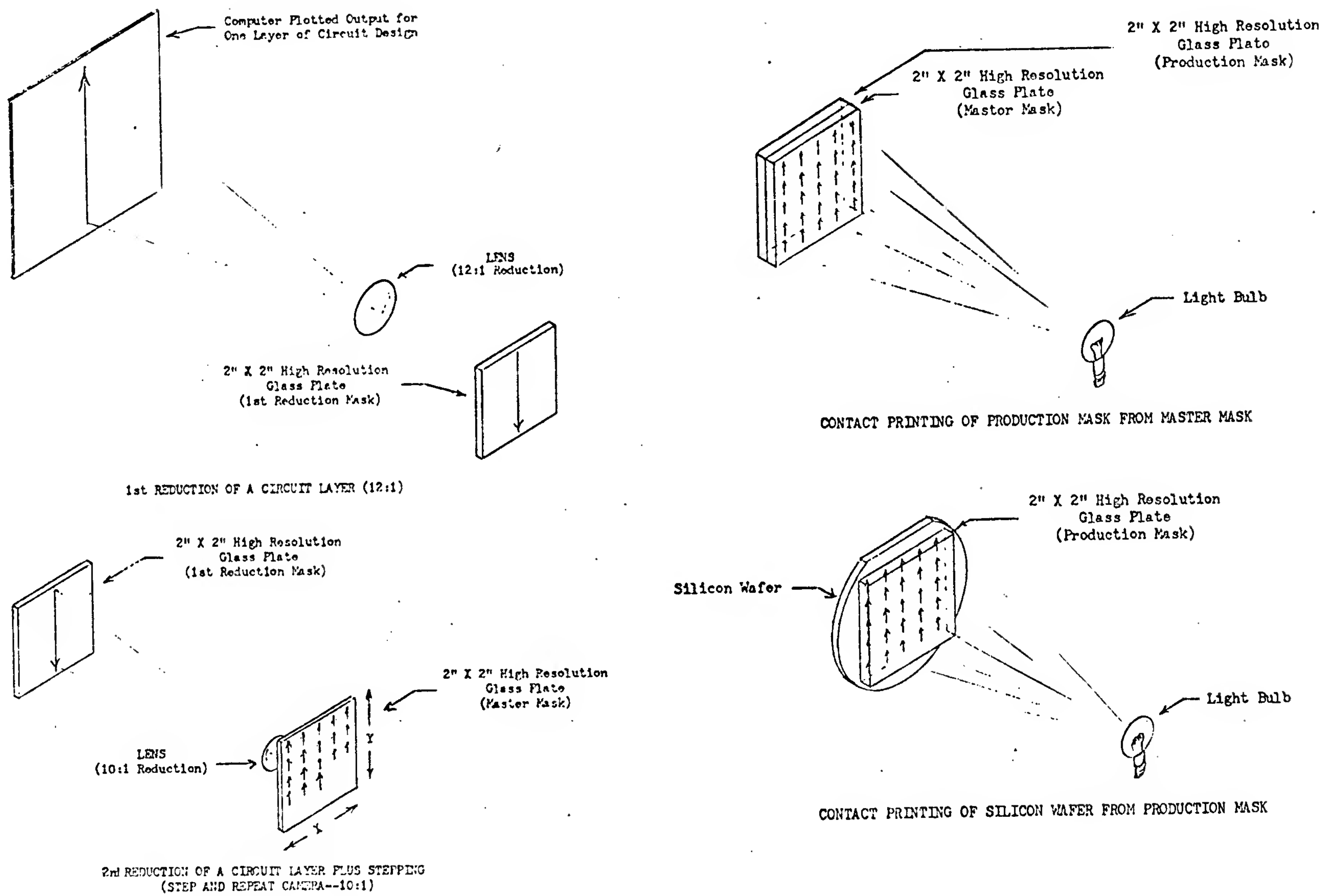

Computer Plotted Output for
One Layer of Circuit Design
LENS
(12:1 Reduction)
2" X 2" High Resolution
Glass Plate
(1st Reduction Mask)
1st REDUCTION OF A CIRCUIT LAYER (12:1)
2" X 2" High Resolution
Glass Plate
(1st Reduction Mask)
2" X 2" High Resolution
Glass Plate
(Master Mask)
LENS
(10:1 Reduction)
Y
X
2nd REDUCTION OF A CIRCUIT LAYER PLUS STEPPING
(STEP AND REPEAT CAMERA--10:1)
2" X 2" High Resolution
Glass Plato
(Production Mask)
2" X 2" High Resolution
Glass Plate
(Mastor Mask)
Light Bulb
CONTACT PRINTING OF PRODUCTION MASK FROM MASTER MASK
2" X 2" High Resolution
Glass Plate
(Production Mask)
Silicon Wafer
Light Bulb
CONTACT PRINTING OF SILICON WAFER FROM PRODUCTION MASK

Figure 3

On December 15, Paul Piper attempted his first definition of the problem. He decided that a successful four barrel step-and-repeat camera was dependent upon the designer's ability to overcome the following problems:

-Registration, which is the alignment between corresponding images in each mask. The distance between any two consecutive images or patterns in any array must be identical in both the x and y directions (Figure 3). The camera should be able to repeat the position at every operation to better then ±50 micro-inches. The movement of the x-y stage must be controlled within this tolerance and the motion must be orthogonal.

-The environment in which the camera is to operate must be controlled. It must first be dust free. The presence of even a one micron dust particle could cause faulty image generation. Temperature and humidity changes could affect the dimensional stability of the elements. Consequently, precise control of temperature and humidity are necessary.

-Because of the precision required the camera must be isolated from vibration, The isolation must eliminate relative motion between object and image plane.

-The reduction ratio must be extremely accurate and identical in all four barrels. With a 10:1 reduction the optical system must be able to resolve a minimum line width of 0.2 mils with high contrast and good edge definition over the entire useful image area, approximately 0.360 inch in diameter.

-The image distortion in each of the barrels must be within the pattern tolerances. The alignment between the optical and mechanical axis must be as accurate as possbile in order to match the resulting mask with other members of the set.

Piper realized that the heart of the system would be the lens. He immediately started an intensive literature search to bolster his knowledge of optics. This search continued throughout the project. He decided that before any further design could be carried out, an optical system must be selected. The optical system would consist of: the illumination system composed of the light source, the condenser, the light filter, the shutter, the filter holder, the light housing and the system support; and the optical column composed of the lens, the lens holder, the object mask holder, the lens object separation column and the barrel support housing.

Early in January 1967 Piper had the purchasing department start a search for a suitable lens. He had set the

requirements as a 10 to 1 reduction with a resolution of 0.2 mils minimum line width with good edge definition; the image field was to be approximately 0.36 inches (object field 3.6 inches). They sent the request for quotation (Figure 4) to approximately 30 manufacturers.

At this time, Roy Nakai, a mechanical engineer, was assigned to work under Piper as a junior engineer. As a result of their studies Piper and Hunt recommended to management that Friden purchase a microphoto-repeater camera from an outside source. This would provide an immediate reliable source of masks for research. This proposal was rejected and the original plan to build was upheld.

Preliminary specifications were set by January 25 (Figure 5). These were the sole design constraints placed on the camera at the outset of the project. Preliminary sketches were made. To estimate the cost of the project Piper divided the design and construction into six major areas: optical barrel, positioning mechanism, support system, image cassette, instrument packaging, and overall evaluation. Each of these areas was further divided into materials cost (Figure 6) and manpower (Figure 7). The materials cost included raw materials plus purchased finished parts. Manpower estimates included time for engineers, draftsmen, technicians and machinists (Figure 8).

The design and construction of a four barrel step-and-repeat camera, Project 355, was approved January 26. This marked the official start of the project. Because the research division needed masks immediately, Project 362, a one-barrel first reduction camera was initiated on January 31. Because of the higher priority of Project 362 it consumed almost all of Piper's and Nakai's attention, completely halting any work on Project 355 for about three months.

All lens quotations were received by early February. The most favorable reply was from the Elgeet Company, Rochester, New York. They proposed to produce four lenses to specification for a total of $6,138. Since performance was guaranteed this seemed an ideal source. A purchase requisition for the lens was submitted to management for approval, but before it could be approved, the Elgeet Company went bankrupt. The search for a lens supplier started again.

The construction of the first reduction camera, Project 362, was completed April 6 and it was producing experimental microcircuits. This freed Piper's team to focus their attention on the four barrel step-and-repeat camera. Piper revised his cost estimates April 10 (Figure 8).

Friden, Inc.
RESEARCH DIVISION
OAKLAND • CALIFORNIA
A SUBSIDIARY OF THE SINGER COMPANY

4 January 1967

James Archer
Space Optics General
1855 W ~~189th~~ 169 Street
Gardena, California 90247

Dear Mr. Archer,

This letter is a follow up to our telephone conversation of 3 January. As we discussed, Friden has a requirement for lenses for use in a step and repeat process to product master masks for use in the fabrication of integrated circuits.

For production efficiency and mask contrast sharpness reasons, it is highly desirable to use photosensitive resists. In that most of these resists are not sensitive within the range of the commercially available lenses, it is necessary to have a lens system designed which is sensitive somewhere within the wavelength bandwidth of 310 - 460 millimicrons.

We at Friden are currently involved with the design and ultimate construction of a multi-barrel (four to six barrels) step and repeat camera system and are at the point where we must decide upon a lens system before continuing with the current design. Therefore, it is necessary for us to obtain performance, delivery and cost data for such a lens system.

Since Friden is not in the lens design business, I shall only give the essential requirements for our needs and leave the design decisions and "trade offs" to the experts. Our basic requirements are:

1. Magnification - 1/10 (Reduction of 10 to 1)

2. Resolution - Lens system must be capable of resolving a minimum line width of 0.2 mils with high contrast and good definision results anywhere within the useful image field.

3. Image field - The diameter of the useful image field (D_F) at a reduction of 10 to 1 for each lens system must be somewhere within the range of $0.15 < D_F \leq 0.36$ inches. It is desirable to have D_F closer to 0.36 inches than 0.15 inches.

4. Wavelength - Lens system must be designed to function somewhere within the wavelength bandwidth of 310 - 460 millimicrons. The design frequency should correspond to that of a commercially available illumination source. It is desirable to have the lens system corrected for a reasonably large bandwidth about the design point.

(cont...)

5. Matching - It is far more necessary to match each lens system (four or six systems) to each other than it is to eliminate all distortions.

6. Cost - Naturally, the costs are to be minimized. However, should design decisions or "trade offs" occur that significantly increase the cost while improving the lens performance from a marginal to an acceptable situation, they are to be identified. Nonrecurring (engineering) costs are to be separated from that required for the manufacturing process. Provide quotes for the four each and six each lens systems.

7. Delivery - Show delivery schedule as referred to receipt of order.

8. Additional information -

In addition to cost and delivery data, please supply as complete as possible design goals which correspond to the following specification items.

a. Focal length.
b. Maximum relative aperture.
c. Aperture scale.
d. Standard magnification 1/10, (10 to 1 reduction)
e. Object size
   1) maximum
   2) useful
f. Image field
   1) maximum
   2) useful
g. Working distance from object to image plane.
h. Wavelength
   1) design point
   2) bandwidth
i. Aerial resolving power (value used to be referenced to same contrast (intensity) ratio.
j. Aperture efficiency at image corner.
k. Distortion of image corner.
l. Lens system mounting.
m. Construction
n. Dimensions
   1) maximum diameter
   2) maximum length
o. Weight
p. Ambient temperature range.

I would appreciate hearing from you as soon as possible. Should it be necessary, you can contact me at (415) 357-6800 Ext. 578.

Thank you.

Sincerely,

FRIDEN, INC. - RESEARCH

Paul V. Piper

PVP: s

Figure 4

Copy of a Letter Requesting a Lens Quote

	Specification	Jan. 1967 Conceptual Design First	June 1967 Second	June 1968 Final Design
1.	Reduction ratio	10:1	10:1	10:1
2.	Resolution/contrast/ edge definition.	This system must have the capability of resolving a minimum line width of 0.2 mils with high contrast and good edge definition, at all points within the useful image field.		Same
3.	Image field.			
	a. Maximum useful image square	0.250"x0.250"	0.170"x0.170"	Same
	b. Maximum useful image diameter.	0.354"	0.240"	Same
4.	Object mask size.			
	a. Basic glass plate size.	4"x5"	2"x2"	Same
	b. Lip of plate	1/8"	15/128"	
	c. Object mask size	2.5"x2.5"	1.7"x1.7"	
5.	Image mask size			
	a. Basic size of glass plate	3"x3" and 2"x2"	2"x2"	Same
	b. Lip of plate.	1/8"	15/128"	Same
6.	Type of photo-sensitive plates	Photo Resist on chrome coated glass plates and high resolution glass plates.	High resolution glass plates.	Same
7.	Image positioning capability			
	a. Max. stepping error	± 50μ in	± 500μ in	Same
	b. Repeatability	± 10μ in	± 50μ in	± 20 in
	c. Min. stepping increment.	0.001"	Min chip size	.010"
	d. Max. depth of focus variation.	± 25μ in	± 50μ in	Same
	e. Range of increments	.01"-.33"	Fixed scale	Increments of minimum chip size.
	f. Type of stepping operation	Automatic	Manual	With semi-automatic control
8.	Camera environment.	Self contained dust-free filter system using dry N_2 atmosphere with automatic temperature control.	Dust free with constant temperature (±1°F) and constant humidity.	

Figure 5

Basic Design Requirements

Task: Optical Barrels (4 each)

Description	Quantity	Unit Cost	Total Cost	Non. Cap. Cost	Capital Cost	Cost Est. Method
1. Illumination Column						
A. Light source						
1. Bulbs (xenon)	4	$ 40.00	$ 160.00			C
2. Bulbs (Press. Hg)	4	30.00	120.00			C
3. Sockets (And Matches both bulbs)	4	6.50	26.00			C&BG
4. Back reflectors, cover and support	4	25.00	100.00			BG
B. Condensor	4	80.00	320.00			C&BG
C. Filter	4	40.00	160.00			C&BG
D. Filter Holder	4	10.00	40.00			BG
E. Shutter						
1. Mechanical parts	4(set)	10.00	40.00			BG
2. Actuator	1	32.00	32.00			C
2. Optical Column						
A. Lens (Catadioptical Reflective system) Elgeet Optical Co. Inc.						
1. Non-recurring Optico Mech. Eng			3578.00			
2. Lens system	4	640.00	2560.00			TQ&LQ
B. Lens Holder	4	30.00	120.00			BG
C. Object Mask Holder	4	25.00	100.00			BG
D. Obj. Mask and Lens Separation Column	4	12.00	48.00			BG
E. Object Shims	4(sets)	10.00	40.00			BG
TOTAL COSTS			7444.00			

C - Catalog Price LQ - Letter Quote
BG - Best Guess TQ - Telephone Quote

Figure 6

Materials Cost Estimate (Optical Barrel Only)

Task: Optical Barrels - (4 each)

Subtask Description	Engineers (Hrs)	Drafting (Hrs) Designer	Detailer	Technician (E&M)	Machinist
1. Illumination Column					
1. Design	48	20	40		
2. Procurement	10				
3. Fabrication				16	48
4. Assembly and Checkout	4			32	
2. Optical Column					
2.1 Object Mask Holder (Includes shims)					
1. Design	40	24	40		
2. Procurement	4				
3. Fabrication and Assembly				4	40
2.2 Lens and lens holder	8	8	16		
2. Procurement	16				
3. Fabrication and assembly				6	48
4. Checkout-Testing (adjustment)				4	
2.3 Object Mask and lens separation column					
1. Design	3	2	4		
2. Procurement	2				
3. Fabrication and Assembly				1	8
TOTALS	125	54	100	63	144

Figure 7

Manpower Estimate (Optical Barrels Only)

	Optical Barrel	Positioning Mechanism	Support System	Cassette (2)	Instrument Packaging	Over-All Evaluation	Total Man-Hours	Total Cost ($)
Original Date: 1/25/67								**Total $60,859**
Engineering Hours (1 hr = $18)	135	172	27	20	373	240	1367	24,606
Drafting Hours (1 hr = $10)	154	114	42	48	308	-	666	6,660
Technicians' Hours (1 hr = $8)	63	144	7	8	422	80	724	5,792
Machinists' Hours (1 hr = $15)	144	60	40	96	124	-	464	6,960
Material Cost ($)	7444	3040	650	100	2800	-	-	16,841
Revised Date: 4/10/67								**Total $57,297**
Engineering Hours (1 hr = $18)	199	268	48	20	43	240	1188	20,384
Drafting Hours (1 hr = $10)	154	114	42	48	308	-	666	6,660
Technicians' Hours (1 hr = $8)	63	144	7	8	422	80	724	5,792
Machinists' Hours (1 hr = $15)	154	84	60	96	124	-	508	7620
Material Cost ($)	7560	3040	650	100	2800	-	-	16,841

<u>Figure 8</u>

Cost Summary-Manpower Consumption

A Nikon lens was obtained on loan from the supplier for evaluation. It turned out to have excellent resolution and distortion qualities. The evaluation prompted Piper to devise a proper test program for all future lenses. Four Nikon lenses would cost $5200. When Piper submitted a purchase requisition for these lenses, his request was turned down by management. The reason given was that the lenses were needed for a specific purpose; the Nikon lenses were considered to be "more lens than needed". This rejection caused Piper to reflect that even if Elgeet had not gone bankrupt the purchase of the Elgeet lenses would not have been approved by his management. Following the rejection of the Nikon lens, a series of other lenses were tested with little success.

A Schneider Xenon lens was purchased in the latter part of April for $61. It proved to have exceptional performance. Four additional lenses were purchased immediately, contingent upon Friden's testing and accepting the lenses. Three of the lenses were acceptable, the fourth was rejected and returned. Another lens was furnished in an attempt to complete the order but it too was rejected. Following this rejection, it was noted that the satisfactory lenses were of the same serial number series, while the rejected lenses were not. The Schneider representative was asked to ship all his remaining lenses in the accepted serial number series for evaluation.

On June 1 Piper called his team together in an attempt to pin down the necessary physical dimensions and to start detail design. The team now included Harold B. Wells who had been hired two weeks earlier as a designer.

Starting from its most basic form, the microphoto-repeater was to have four lens systems. The image plane was to move in two orthogonal directions, x and y, perpendicular to the optical axis. The object plane was to be fixed. The assumption was made that Schneider Xenon lenses would be used and that all would perform as well as the lenses in hand (Figure 9).

The first decision made was to fix the relative location of the optical components. Three configurations were available: "horizontal orientation" with the optical axis parallel to the horizontal plane; and two vertical orientations (Figure 10); "image plane down" with optical axis vertical and the image plane below the object plane; and "image plane up" with optical axis vertical and the image plane above the object plane. The image plane down configuration was standard for most commercially available microphoto-repeaters.

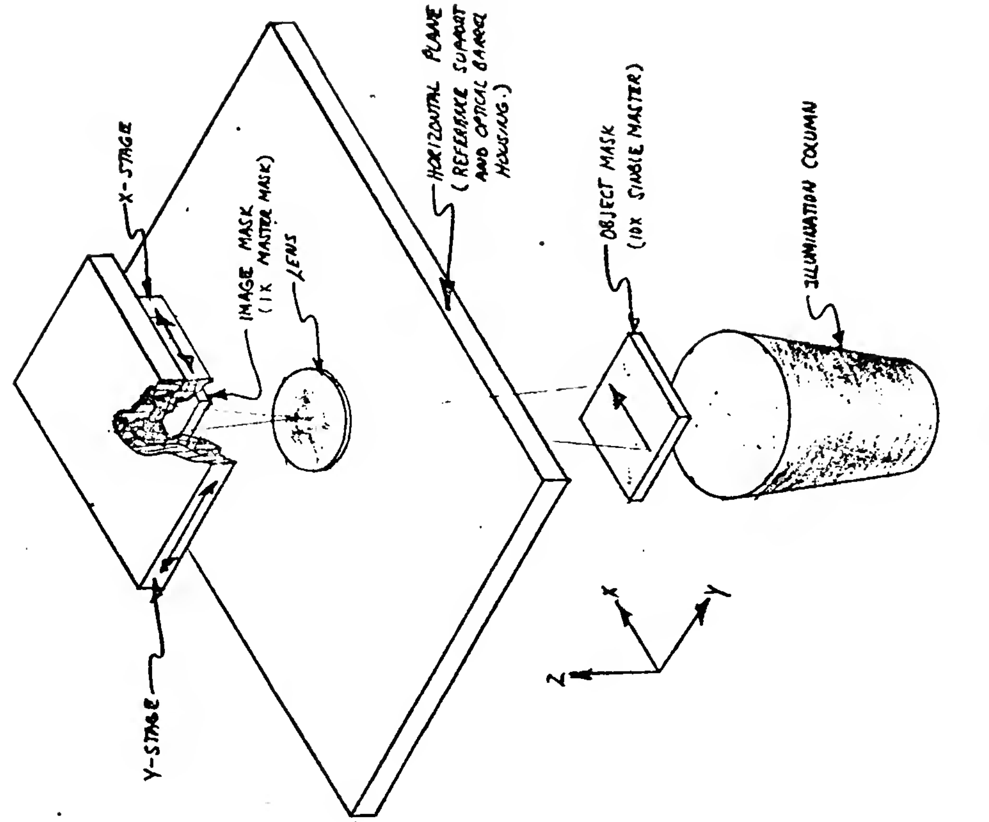
1. Focal length = 28mm (nominal), (E.F. = 29.4mm ± 0.2mm)
2. Maximum aperture = F 2
3. Aperture scale: 2, 2.8, 4, 5.6, 8, 11, 16
4. Magnification = 1/10
5. Object size = 287mm (92mm with resolution better than 300 lines/mm
6. Image size = 28.7mm (9.2mm with resolution better than 300 lines/mm)
7. Resolution = 400 - 500 lines/mm
8. Overall working distance (obj. - im. dist) = 355.7mm (14.01")
9. Wavelength = 366 - 687 mμ
10. Mounting = thread
11. Dimensions:

    Max. Diameter = 37.5mm

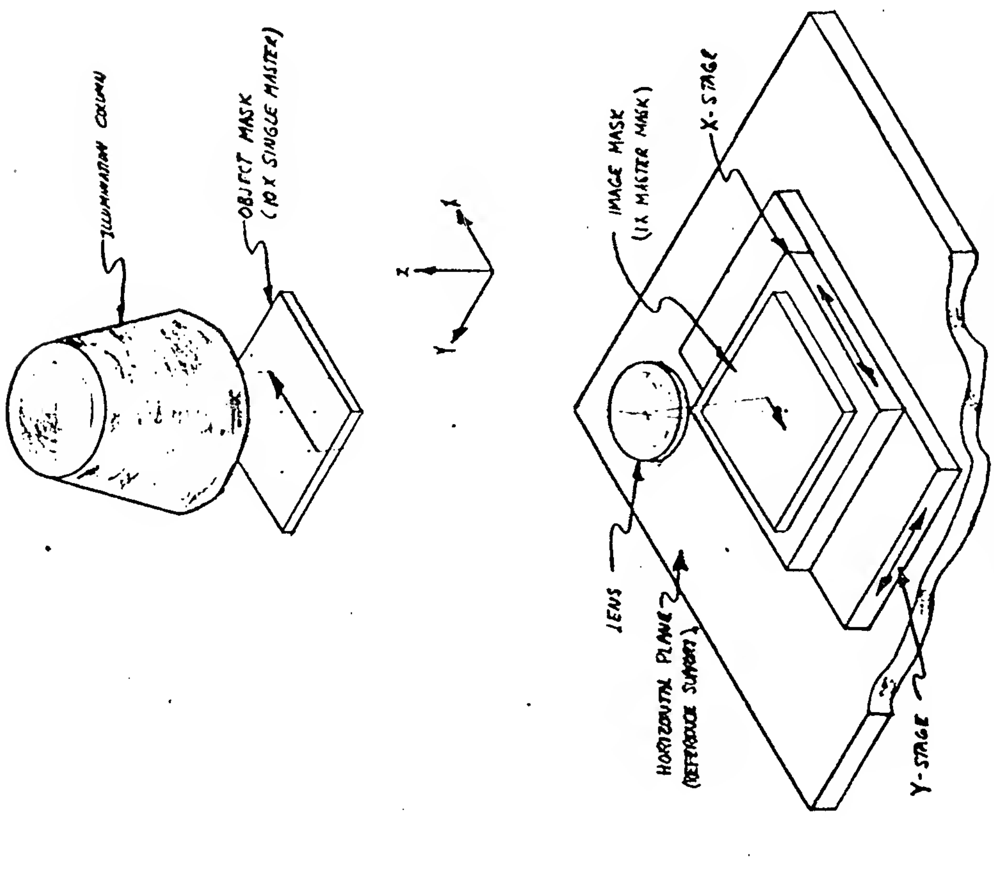
    Max. langth = 23.8mm
12. Weight = 67 grams
13. Cost = $61

Figure 9

Schneider Xenon Lens



VERTICAL ORIENTATION — IMAGE PLANE UP



VERTICAL ORIENTATION — IMAGE PLANE DOWN

Figure 10

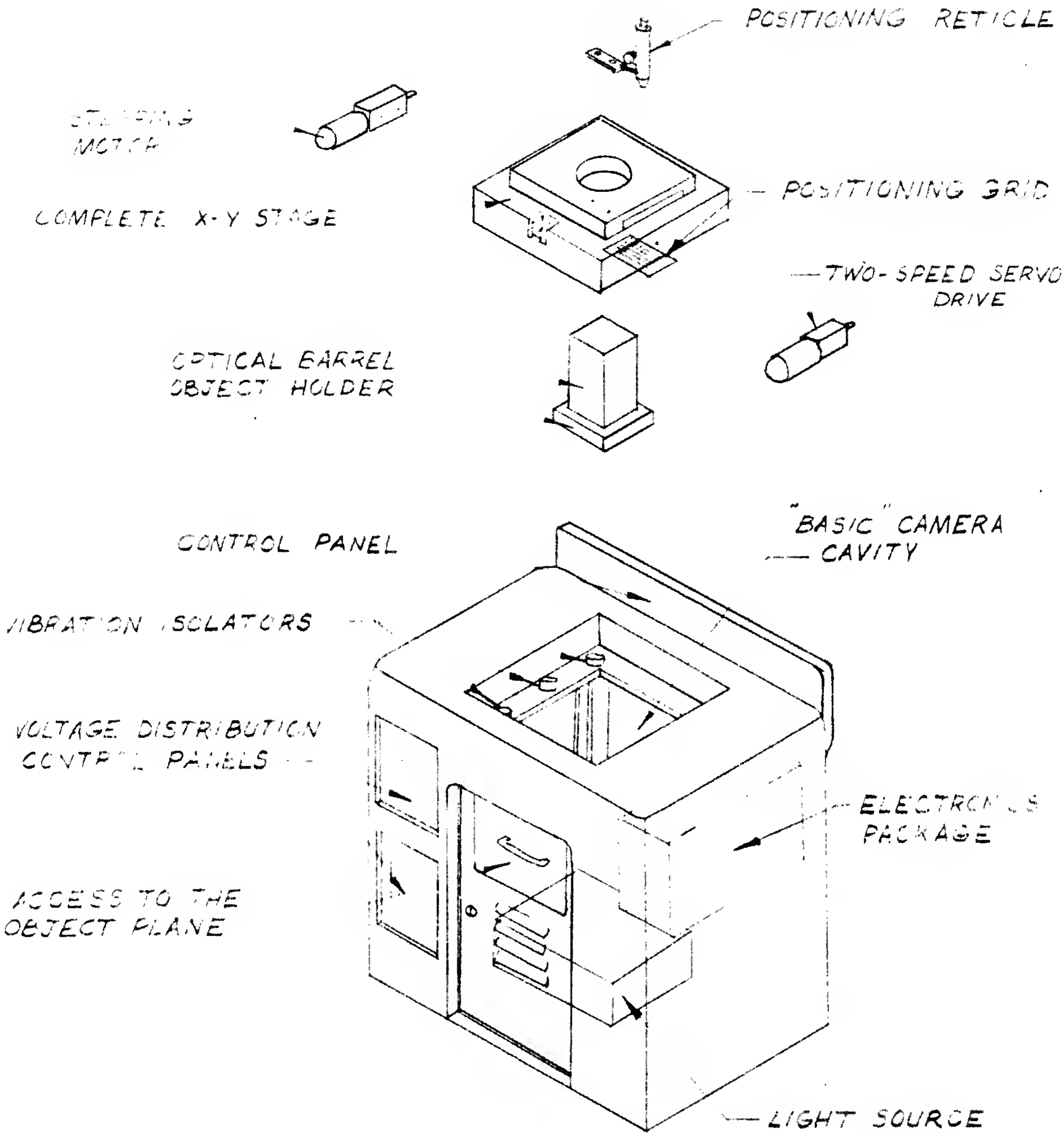
The image plane up configuration was chosen as the best. It promised the most compact construction of the three, particularly for the short focal length lens. The geometry was simple. This configuration required the emulsion on the image plate to be facing downward, therefore, it was potentially dust free. The image cassette being on the top provided a convenient working height. Light shielding could be provided with the image plane up configuration without the use of bellows.

On the basis of the above a preliminary schematic was made (Figure 11). The combined optical barrel and object holder was to be attached to a granite reference block which was isolated from the main frame. The image cassette would be attached to the x-y stage. This stage was to give controlled motion in two exactly orthogonal directions parallel to the horizontal plane. The first reduction masks on 2" x 2" glass plates acted as objects and were to be located securely in a drawer at the bottom of the optical barrel.

The lens was focused by moving the lens in the vertical direction. Gimble mounting about two axes would permit alignment with respect to the x-y plane. The light source was to be two rows of mercury vapor lights. A diffuser plate was to provide a uniform light intensity with variation of less than 5% over the entire object plane, eliminating the need for a condenser system.

Consideration was given to controlling the exposure time by simply switching the light source off and on. It would have been effective and economical, but this would have limited all barrels to the same exposure. Anticipating that different exposures might be desired at each barrel because of different object film density, a spring loaded solenoid operated leaf shutter was included for each barrel. To detect faulty operation a photocell was to be included on each shutter triggering an optical and audible alarm.

The function of the step-and-repeat camera is to reproduce multiple duplicate images onto a single production mask. Since the images are to be superimposed in production it is important that the relative location of the repeated image be identical from mask to mask. Two types of errors are possible in the stepping process: 1) Reproducible error which is constant, is dependent on the geometry and construction of the stepping mechanism. The reduction of the magnitude of this error results in increased cost. Reproducible error will be the same from mask to mask and does not have an adverse effect on manufacture of masks but may affect later processing of circuits, such as cutting and testing. 2) Random error varies with each step. Its presence can be attributed



<u>Figure 11</u>

Schematic of the Final Design

to operator skill, system backlash, etc. The use of four barrels eliminates the effect of random error between a set of four masks which are made concurrently. The x-y stage was to be driven by servo motors,manually controlled. Two drive rates would be required: gross motions from step to step and fine motions for exact location. A positioning grid was to be attached to the fixed stage and a reticule microscope to the moving stage.

The four high reduction glass plates on which master masks are generated was to be housed in a cassette which has metal shields to protect the masks from light during transport.

To operate the system the cassette is loaded on top of the x-y stage in the square opening. The cassette shield is retracted. Initially the x-y stage is positioned over the reference point using the reticule microscope. Depending on the direction of motion required, the corresponding step motor is operated. The coarse motion is accomplished automatically by the electronic control. The exact location is then set by viewing the positioning grid through the microscope and manually controlling the servo motor at the fine translation rate. The ability of the operator to match the reticule to the positioning grid is the main source of random error. After exact location the x-y stage is locked to the reference block. The shutters are then operated exposing images from the first reduction masks on to the four production masks. The stepping and exposing operation is repeated as many as 100 to 1000 times to complete one set of production masks.

The basic camera had to be a rigid unit isolated from the building and other external vibration. Three sets of isolators were to be used, each designed to eliminate a frequency range. The set nearest the camera would eliminate the high frequencies and the set furthest from the camera would eliminate the low frequencies.

Temperature effects were to be eliminated by maintaining a constant temperature of 68° in the critical regions. The heat generated by the electronic equipment and lights was removed by separate forced-air systems, thermostatically controlled. The region near the cassette must be maintained at 68°F ± 1°F. To facilitate temperature control, it was decided that the unit would be housed in a temperature and humidity controlled room.

The camera was to be built into an integral frame housing the camera, its necessary electronic package, and the power supplies. The electronics package was to operate the camera,

the position and exposure controls, as well as the interlocking safety and alarm systems. Piper felt that "A device that is inherently difficult to operate is nearly useless regardless of the care which has been taken in designing the major components. The operating controls and their location would therefore be selected with human factors in mind so that "natural operation" is achieved. Although not incorporated in the present design, consideration will be given to future incorporation of an automatic positioning system. The present design would incorporate a fully automatic "origin return".

Several useful indicating systems would have to be incorporated. An audible and visual alarm for camera malfunction was desirable. An x-y position indicator relative to the origin, an exposure meter, and lights indicating sequence operation were desired. Malfunction interlocks would prevent double or false imaging.

The layouts were finished and outline drawings completed June 16. Many of the working drawings had also been prepared. The design was then submitted to management for approval. It was rejected because the unit was too large. The exact reasons for this rejection were never explicitly "pinned down" but Piper felt that the Friden management expected a more compact camera because of their familiarity with commercially available units. Such units were advertised as being 24 inches high by 18 inches square. However, these units did not contain any of the electronics, controls, or power supplies which are purchased as separate assemblies. Piper felt his design was prejudiced because it was self-contained.

As a consequence of the rejection the specification was revised on June 19 (Figure 5). The new specification reflected the desire for a smaller unit by reducing the required mask size by one-half. The deadline for the completion of the new design was September. Roy Nakai was given the task of designing the x-y guide mechanism. The accuracy of the x-y stage was considered critical to the success of the unit.

At that time the Research Division hired its first model-shop man. This indicated their committment to manufacture their own hardware.

Six Schneider Xenon lenses were received on July 18. They were all accepted. Piper now had ten satisfactory lenses. The discovery of these "better than average" lenses could be called a lucky chance, since other lenses made by Schneider Xenon did not meet the specifications. The evaluation and resolution matching of the Schneider Xenon lenses was completed in August. The four lenses with resolution and distortion patterns as nearly equal as possible were chosen for use in the camera.

To document this important selection and testing procedure Piper and Rowland who had helped perform the tests prepared a formal report. This turned out to be the first formal report documenting results of tests in Friden Research Division. The report was completed and submitted October 9.

Meanwhile the preliminary redesign for smaller physical size was completed July 25. Although the maximum mask size had been reduced by one half, the overall physical dimensions had changed only slightly. This was due to the fact that the electrical and electronic components had not changed. In spite of this the design was approved by management.

In early August the fabrication of parts was begun and by September the design had proceeded sufficiently that a modelshop man was assigned to work exclusively on Project 355 for Piper. By October 1 all working drawings were finished and production was in full swing.

Nakai's design for the x-y stage was a conventional one (Figure 12) and Piper did not feel it would fulfill the accuracy requirements. This led to a conflict within the design group.

Nakai was finally removed from Project 355 on October 11 and Piper took over responsibility for the design himself.

Piper was faced with two alternatives to achieve the desired straightness and orthogonality. He could modify the existing and accepted design by using extreme tolerances or devise an entirely different, inherently more accurate approach. The conventional mechanism requires that the motions be perpendicular to one another and, at the same time, that the planes of their motion be exactly parallel. This imposes critical precision and alignment problems during manufacture and assembly. The conventional design could only be made to work at great expense. Therefore, Piper elected to devise another approach.

By taking a fresh approach Piper devised a kinematically different mechanism which separated the elements controlling the parallel plane motion from the elements controlling orthogonality. The use of air bearings gave smooth free movement that locked simply by turning off the air. By the first week in November the design of the x-y stage was completed and Do-All Science Center Inc. was given the contract to produce it.

Piper now turned his attention to the x-y stage drive. This mechanism must be capable of imparting incremental linear motion with precision commensurate with the positioning

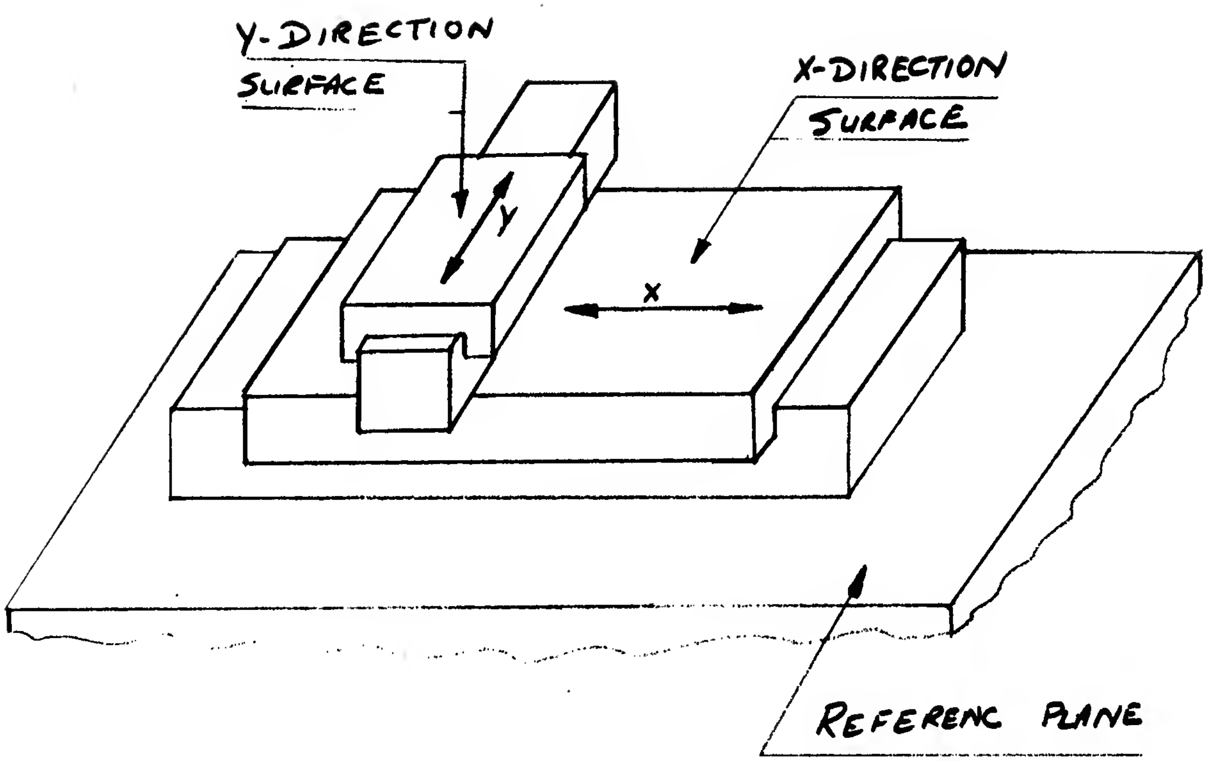


Figure 12

Conventional X-Y Positioning Stage

tolerance of the image plane and the travel time for gross steps must be reasonable. He concluded that the mechanism must incorporate both a coarse rapid travel and a fine positioning motion. One conventional system using stepping motors (Figure 13) produced rapid travel by speeding up the stepping rate for rapid travel. This would require additional costly and complicated electronic controls. An alternate system produced rapid travel by over-driving with a separate motor for high speed and used the stepping drive for fine positioning. The high speed required in these mechanical components leads to excessive wear and loss of precision.

After examining many alternatives, Harold Wells came up with an ingenious design early in December. He used a stepping motor and an electromagnetic clutch-brake and by applying a differential drive he was able to achieve the following performance:

Steps per revolution of motor	160
Linear output per step, coarse mode	0.0005"
Linear output per step, fine mode	0.0000028"
Repeatability	±0.000020"

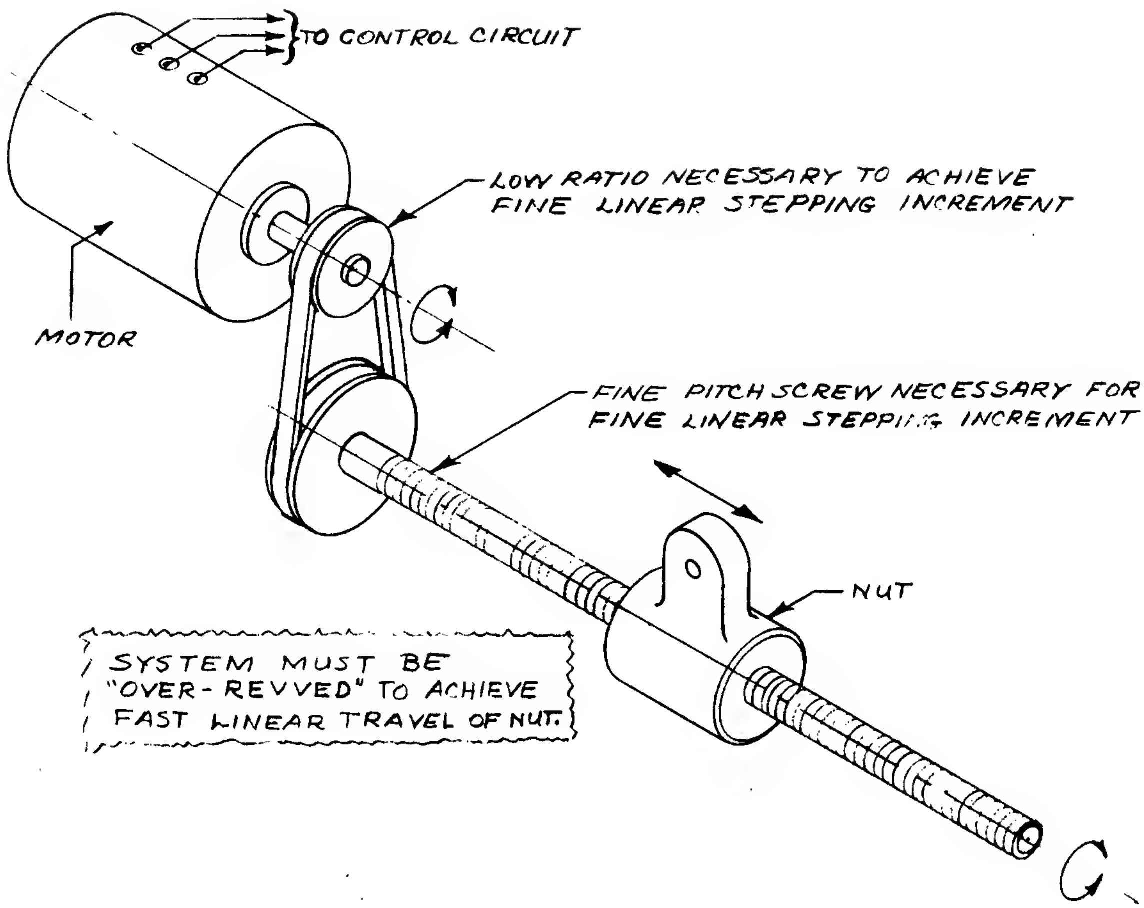
The mechanism was directly coupled to the drive motor and the entire unit packaged into a space 4" by 2-1/2" diameter.

Piper accepted the completed x-y stage at Do-All on January 19, and personally carried it back to the Friden Research Center (Figure 4). The components were made of granite with a surface flatness better than 20 micro-inches for the air bearings. All the plates had a central square cut-out to accommodate the optical barrels.

In January 1968 Piper had to revise his cost estimates upward a second time. He now estimated that material cost would be $19,700 and labor a total of 130 man weeks. Piper was informed at this time that the firm intended to design and build a second generation of the step-and-repeat camera to capitalize on their experience with the first. The new camera was to incorporate automatic positioning.

Piper found that the transition from working drawings to finished hardware presented many problems he could not have foreseen. They not only affected the completion date but left their mark on the success and efficiency of the project.

On March 2, 1968, Friden Research moved from Oakland to a new building in Palo Alto. The dust associated with the new building delayed the assembly and alignment of the camera. The change in locality meant an almost complete change of machine shop personnel. This break in continuity essentially halted production of machined parts.



READ & UNDERSTOOD	DATE	SIGNATURE OF INVENTOR	DATE
[illegible]	[illegible]	[illegible]	Feb. 26, 196[illegible]
E. M. [illegible]	Feb. 26, 1968		

Figure 13

Conventional Linear Servo-Drive System

The movers dropped the assembled x-y stage onto a concrete floor during the move to Palo Alto. It was not damaged but it had to be checked again. During the installation of a mounting bolt into the main base of the x-y stage, a piece was chipped off the bearing surface. It had to be carefully epoxied back into place and the surface hand honed to its original flatness. Problems in the positioning control logic were encountered. Although not entirely expected Piper felt that it was not unusual with new electronic circuitry. Due to these and other problems the total manpower consumption jumped to 151 man weeks by May 17, 1968, 20 man weeks greater than the last estimate.

By the end of June the camera was sufficiently aligned to allow preliminary test. The tests showed that parts of the basic camera design and construction were inadequate. The object holder repeatability was unsatisfactory and an error had been made in fabricating the lens barrels. The image distance was two inches longer than specified. These required a major rework. After considering all the alternatives it was decided to convert to individual pulse Xenon light sources with a condenser and exposure control for each barrel. The object carrier would thus be eliminated and a simple slide holder for each barrel substituted.

With the modifications and corrections underway, Piper looked forward to the completion of the project and contemplated the design of the second generation camera. He felt that he was in a position to do a much better job on the new camera. The intelligence necessary to design the automatic stepping feature would be a direct result of experience gained from designing rather than purchasing this first camera. He felt this vindicated management's decision to build rather than purchase the first camera. A great deal of knowledge and experience had been gained in the field of optics and the requirements and limitations of the reducing process. Such valuable information could not have been gained if a camera had simply been purchased. Piper felt that when Friden went into production on microcircuits the necessary microphoto-repeater would be purchased but the experience gained with their own design would be invaluable in selecting the most suitable unit to give the best automated facility.

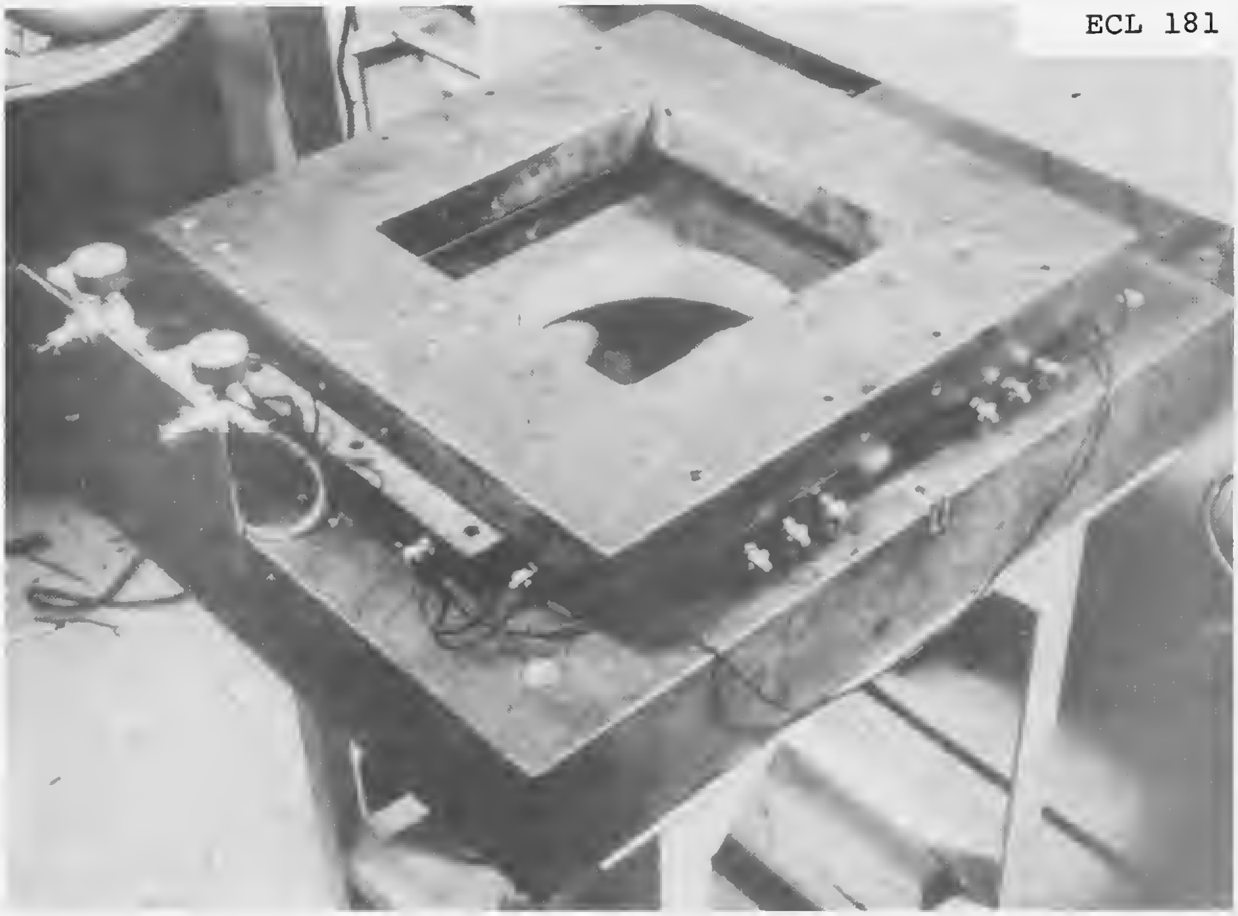


Figure 14 - The X-Y Stage

Figure 15 - The Cassette

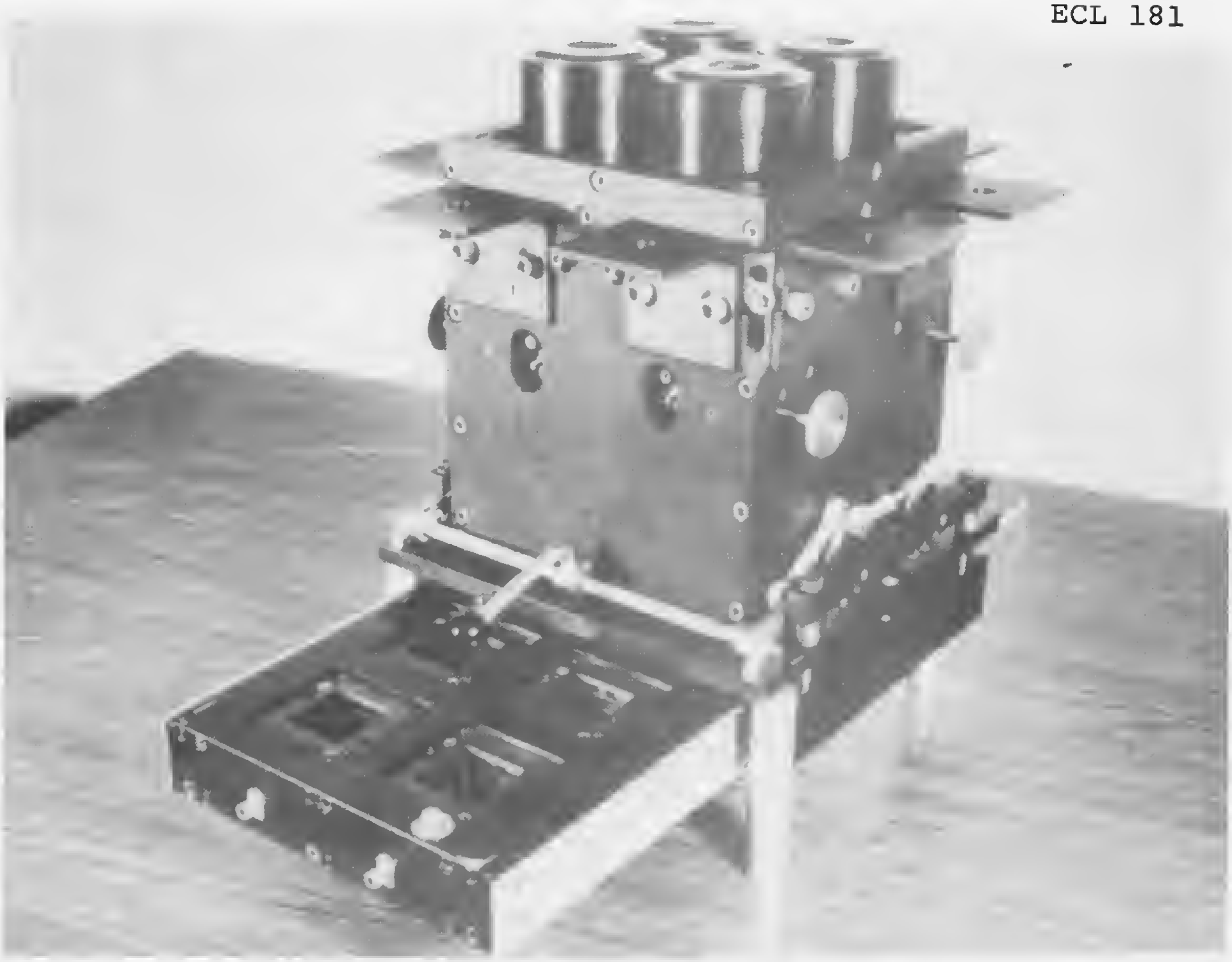


Figure 16 - Lens-Object Holder

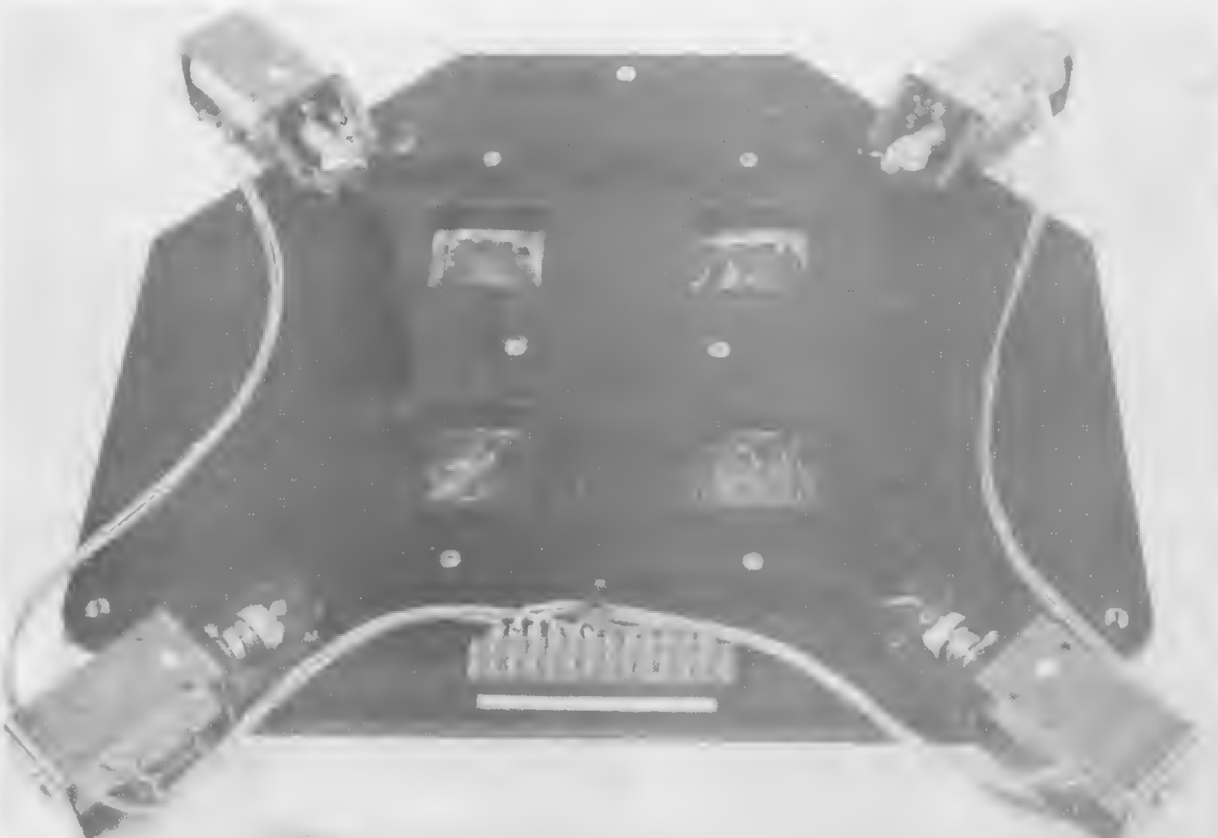


Figure 17 - Shutter Mechanism

Figure 18

Finished Camera

INSTRUCTOR'S NOTE

Four Barrel Step-and-Repeat Camera

This case records the events in the design and production of a camera for making microcircuit masks. It can be used to show the student how management decisions (make or buy), costs, luck (Schneider Xenon lens), interpersonal relations (Nakai), and extraneous events (moving) can affect a project. In reading the case it can be seen that while technical excellence was mandatory, many of the critical decisions were governed by other considerations.

Class discussions can be centered around:

1. The merit of the make-buy decision.
2. Management's rejection of the expensive lens.
3. The need for formal reports in a company.
4. Could the unexpected problems have been anticipated and avoided? How?
5. Who should be charged with the increase in cost?
6. Was the building of the camera as useful as indicated?
7. Schedule for the next generation camera.

The detail solutions in the design have been deliberately omitted from the case. The design of a suitable x-y stage, the design of a drive mechanism or the location and selection of vibration isolators can be assigned as student design problems or projects. The solutions to these problems used in the actual design are given in the attached Figures 19, 20, and 21.

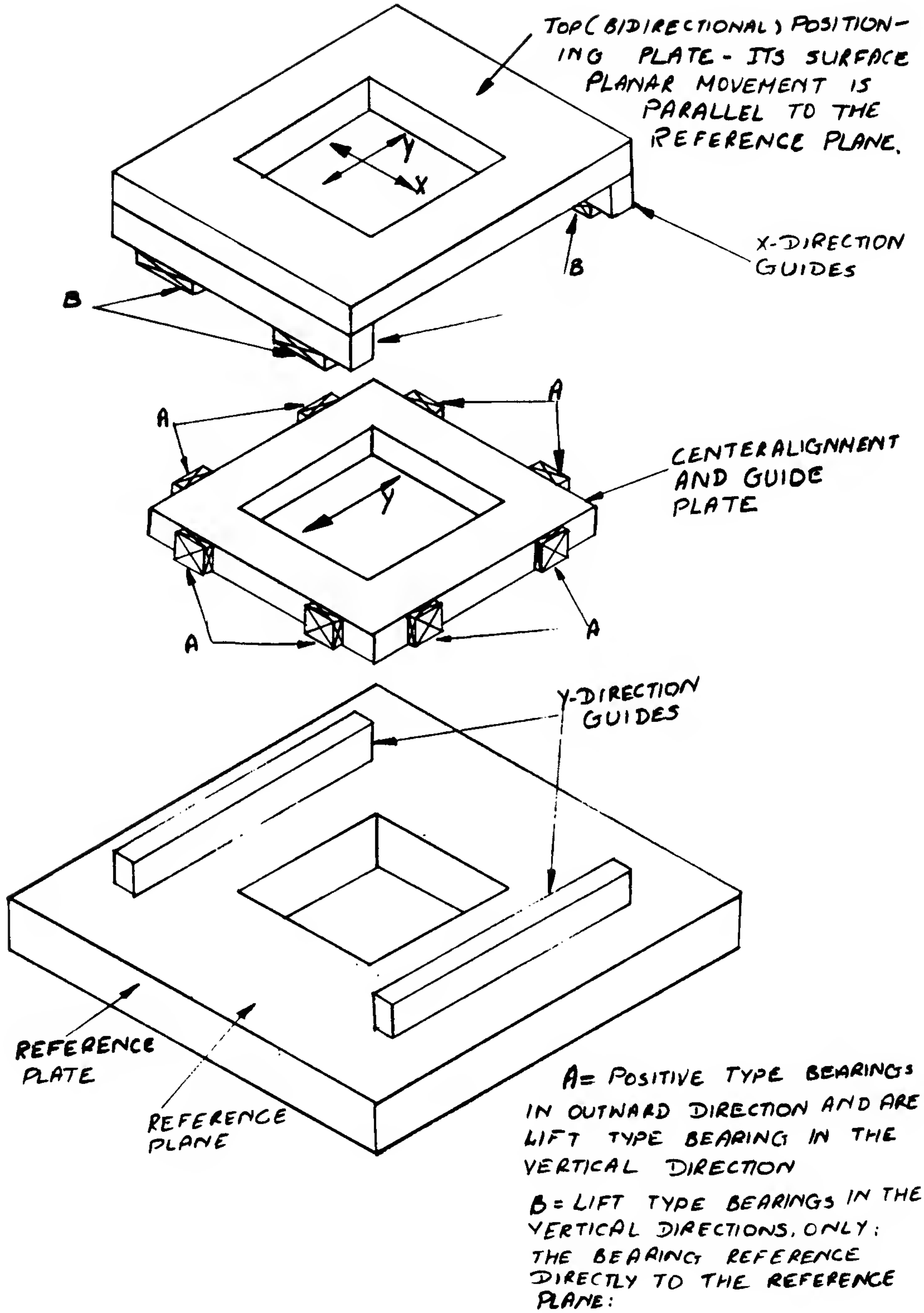
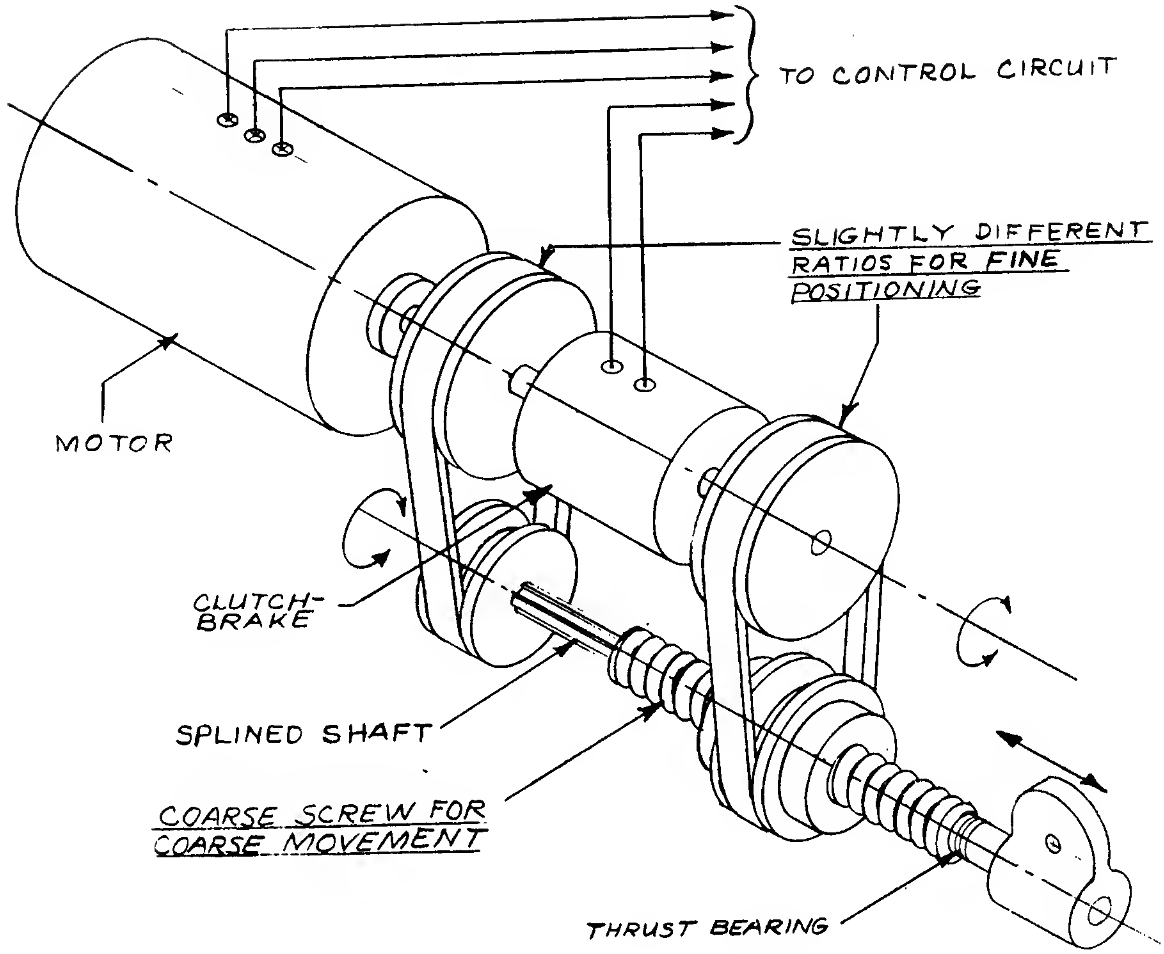


Figure 19. Exploded Conceptual View of the Co-Planar Positioning X-Y Stage With Center Cut-Out

SHEET NO. 3
OF 5 SHEETS



READ & UNDERSTOOD	DATE	SIGNATURE OF INVENTOR	DATE
[illegible]	[illegible]	[illegible]	Feb. 26, 1968
E. M. [illegible]	Feb 26, 1968		

Figure 20

Two Speed Linear Servo Drive
Using Differential Principle

VIBRATION ISOLATION TECHNIQUE

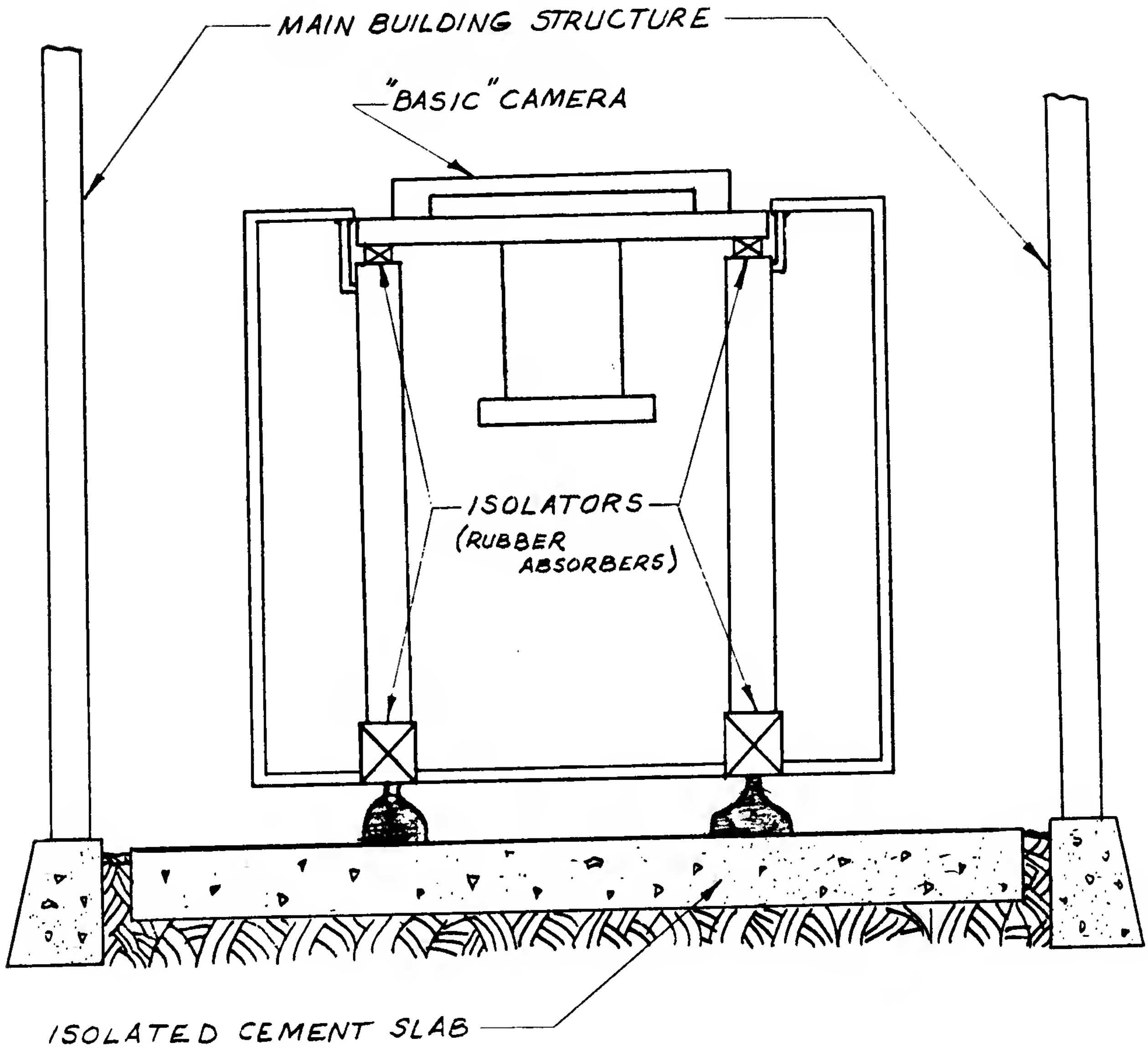


Figure 21